EXCITED STATES OF ^{98}Rh AND ^{99}Rh FOLLOWING THE DECAY OF Pd ISOTOPES

By M. Gąsior, A. W. Potempa, H. Roth and J. Sieniawski

Institute of Nuclear Physics, Cracow*

(Received February 6, 1971)

Energies and intensities of conversion spectra were measured with a magnetic beta-ray spectrometer. Gamma spectra were obtained by the use of a Ge (Li) detector. Schemes of the low excited states of ^{98}Rh and ^{99}Rh are suggested.

1. Introduction

The short-lived isotopes ^{98}Pd (17 min) and ^{99}Pd (21 min) were discovered and preliminarily investigated in the years 1955 and 1956 [1, 2]. The rather complicated chemical extraction of palladium from targets permitted only the simple and coincidence gamma spectra to be measured with the use of NaI(Tl) counters, and a proposal of the decay scheme of ^{99}Pd to be put forth. No transitions associated with the decay of ^{98}Pd had been observed, however. This is why these Pd isotopes have been studied once again now by measuring the spectra of internal conversion electrons and gamma-rays. On the basis of the determined energies and absolute intensities of transitions schemes of the low-lying excited states of ^{98}Rh and ^{99}Rh were derived. Preliminary results concerning the short-lived Pd isotopes were made public at the conference on nuclear spectroscopy held at Dubna, USSR, in July, 1969 [3]. While the results were still being elaborated a paper was published [3] which gives the relative intensities of several of the strongest gamma lines measured in the decay of ^{98}Pd and ^{99}Pd by a Ge(Li) detector. A more systematic measurement of the simple and coincidence gamma spectra of the ^{99}Pd decay was later performed in the work described in Ref. [5].

2. Pd source production

The Pd isotopes were produced in (α, xn) reactions by irradiating metallic ruthenium targets with alpha particles in the U-120 cyclotron at the Institute of Nuclear Physics in Cracow. The targets were about 100 mg/cm^2 thick, and the ruthenium had a natural

* Address: Instytut Fizyki Jądrowej, Kraków 23, Radzikowskiego 152, Poland.

isotopic composition. A beam of approximate intensity of 10 μA was applied for one hour, the particle energy being about 25 MeV. Measurements employed carrier-free Pd sources obtained by the method of vacuum distillation of the target material [6]. This rapid method of extraction let measurements to be initiated some ten-odd minutes after conclusion of irradiation.

3. Conversion spectrum measurements

Internal conversion electrons were measured with a toroidal spectrometer [7] adapted for rapid spectrum measurements, with a time in second region at a point [8]. Figure 1 gives an example of a spectrum measured at a resolving power of 1 per cent and transmission

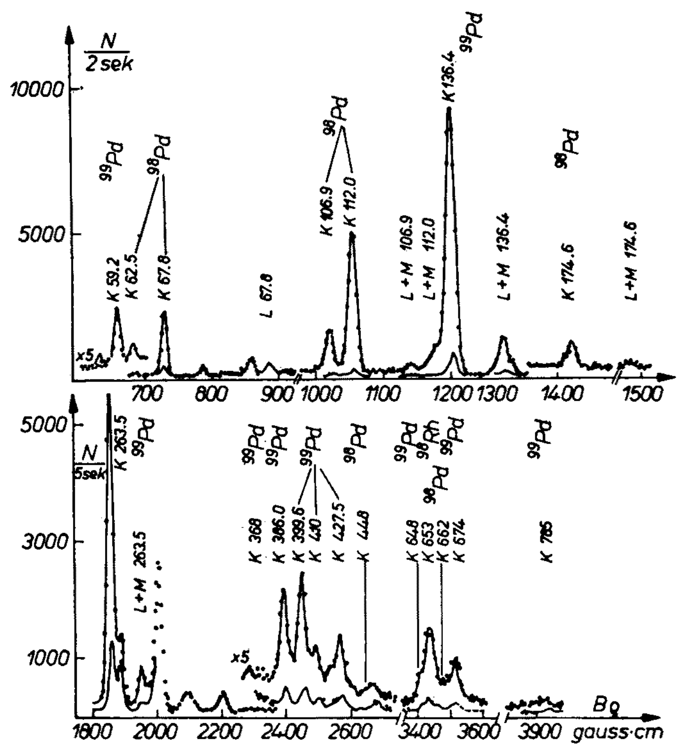

Fig. 1. Two successive conversion spectra observed in the decay of ^{98}Pd and ^{99}Pd at an interval of approx. 30 min

of approx. 20 per cent. To identify the transitions coming from the various isotopes, the half-lives were determined from three successive spectra (Fig. 2). The results concerning the relative conversion line intensities are arranged in Table I and Fig. 3. The spectra also exhibit the known lines from the decay of ^{100}Pd, ^{101}Pd and ^{103}Pd as well as those arising in the source ^{98}Rh, ^{99}Rh, ^{100}Rh and ^{103m}Rh.

TABLE I

^{98}Pd (17.7 min)

E_γ keV	I_γ	$I_{e-}(K)$	$\alpha_K \times 10^3$	Multipolarity	Branching %
62.5	0.18±0.07	0.4	1000	(M1)	0.2
67.8	14 ±4	39.6±1.6	880±270	M1	16.0
106.9	33 ±6	33.6±2.5	260±70	M1	16.6
112.0	100	100	225±50	M1	62.5
174.6	6.5±2.0	3.3±0.5	75±24	M1(+E2)	4.3
661.7	30 ±2	0.56±0.12	2.7±0.7	M1, E2	15.4
^{99}Pd (21.4 min)					
59.2		0.7 ±0.3			0.2
136.4	100	100	140 ±18	M1	87 ±5
263.5	28 ±2	5.2 ±0.2	24 ±3	M1	22.3±3
293.3	1.8±0.4	⩽0.1	⩽7	E1	1.6
368	0.6	0.07±0.02	15.5	E2(M1)	0.6±0.2
386.0	5.8±0.4	0.44±0.03	9.6±1.5	M1(+E2)	4.3±0.3
399.6	6.6±0.5	0.52±0.03	10.1±0.8	E2	5.4±0.4
410	3.5±0.4	0.19±0.03	6.7±0.9	M1(E2)	2.9±0.4
427.5	4.3±0.4	0.29±0.02	8.2±1.4	E2	3.5±0.3
648	3.4	0.09±0.04	3.5±2	M1 E2	2.8±1
673	19 ±3	0.38±0.04	2.6±0.5	M1 E2	15.4±2.5
785	5 ±1	0.07±0.02	1.7±0.4	M1 E2	4.2±1.5
810	1.8				1.5

4. *Determination of conversion coefficients*

Gamma spectra were measured simultaneously with the conversion spectra. These gamma spectra measurements were performed with a germanium detector of volume 2 cm^3 and resolving power of 5 keV for the 662 keV line. Detector calibration (Fig. 4) was done with the use of sources of known gamma transition intensities, ^{75}Se [9], and the ^{101}Pd appearing in the investigated sources [10]. The intensities of the observed gamma lines are to be found in Table I.

Calibration measurements were performed in order to determine the absolute values of α_K. The assumed standard was the 212 keV transition from the decay of ^{121m}Te of a very well known value of coefficient $\alpha_K = 0.0842 \pm 0.0014$, Ref. [11]. The conversion coefficients obtained thus are given in Table I, while in Figs 3, 5 and 6 the obtained results are compared with the theoretical data of Hager and Seltzer [12].

5. *Decay schemes*

In order to arrange the decay schemes of the excited states all possible sums and differences of energies of the observed transitions were analyzed, what with an accuracy of measurements of 0.2–0.5 keV enabled a number of cascades to be revealed. At the same time

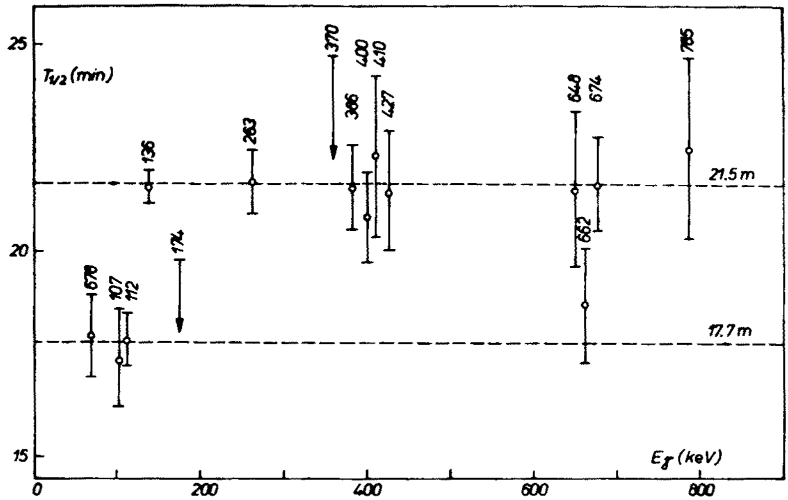

Fig. 2. Half-lives of conversion lines from the decay of ^{98}Pd and ^{99}Pd

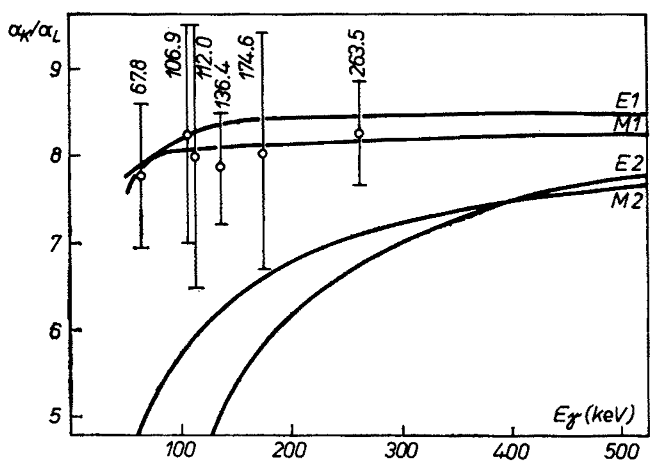

Fig. 3. Values of a_K/a_L for some transitions of the ^{98}Pd and ^{99}Pd decay

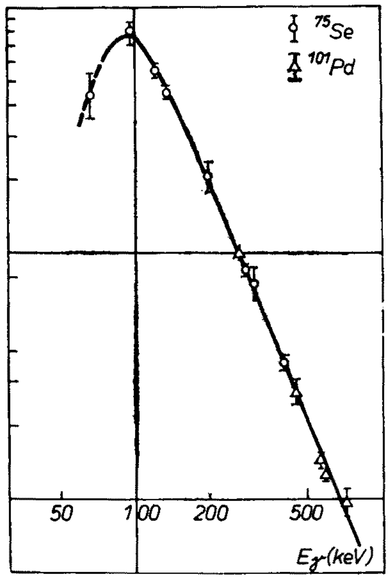

Fig. 4. Relative efficiency of germanium detector

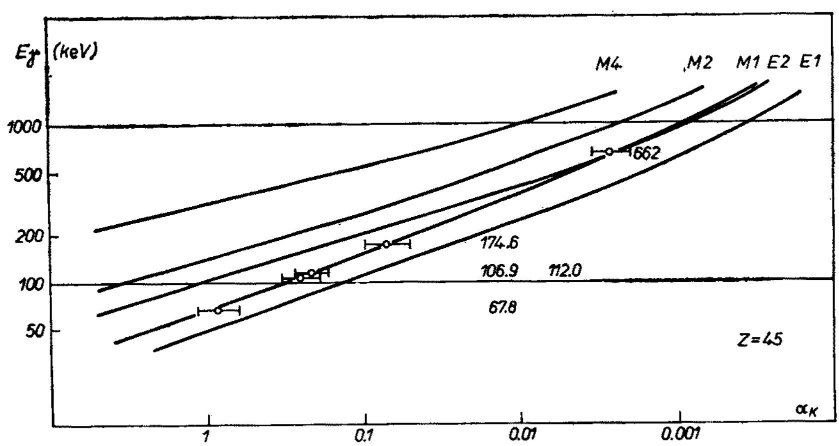

Fig. 5. α_K for transitions in the decay of ^{98}Pd

their absolute values were determined by using the rather well-known decays of ^{98}Rh and ^{99m}Rh for the purpose of checking the intensity ratios of the transitions. Numerical values are given in Table I.

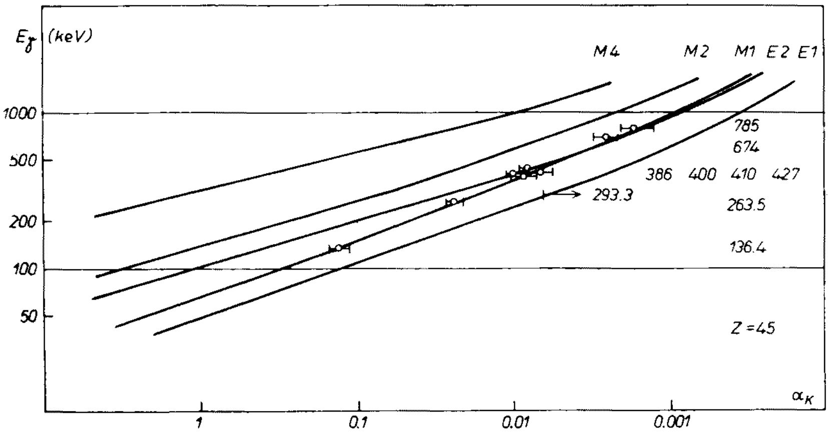

Fig. 6. α_K for transitions in the decay of ^{99}Pd

6. *Excited states of ^{99}Rh*

16.1 d isomeric state

Decays of both states of ^{99}Rh of decay times of 4.7h [1, 13] and 16.1 d [14] are known, while the total decay energies determined in these studies allowed their energy gap to be found, namely, $\Delta E = 3 \pm 30$ keV. At such a low energy and with the competing β^+ decay it is in practice impossible to observe the isomeric transition, the energy of which would uniquely establish the position of the two states.

When examining the spectrum of electrons from the Pd source thirty days after the Pd extraction, the K line from the 89.3 keV transition in ^{99}Ru, enhanced in the decay of the ^{99}Rh (16.1d) isomeric state, was observed. The intensity this transition shows that this state becomes populated by $3.8 \pm 0.5\%$ on the ^{99}Pd decay. Owing to the high forbiddenness ($\Delta I = 2$ with a change of parity) this is not a branch of the β^+ spectrum, nor is it populated from one of the states of spin $7/2^+$, $5/2^+$ and $9/2^+$ by a transition of the M2 or E3 type. This population is most probably caused by transitions from the $5/2^-$ and $3/2^-$ states, like in ^{103}Rh [15] and ^{101}Rh [16].

136 keV state

The M1 multipolarity of the 136.4 keV transition and log ft value of 4.7 for the β^+ transition to this state determines its spin as $7/2^+$.

370 and 429 keV states

The occurrence of the $59.2 + 368 = 427.2 \pm 0.5$ keV cascade and the 427.5 keV transition, taken together with the aggregate intensity of the 368 and 427.5 keV transitions equal to $4.1 \pm 0.5\%$, explains the population of the ground state. The branching of the decay to these states with the respective $\log ft$ values $\geqslant 7.7$ and $\geqslant 6.1$, and the E2 character of the 427.5 keV transition, implies that the spins are $3/2^-$ and $5/2^-$.

400 keV state

The presence of the $263.5+136.4=399.9\pm0.3$ keV cascade and the E2 character of the 399.6 keV transition show that the spin of this state is $5/2^+$.

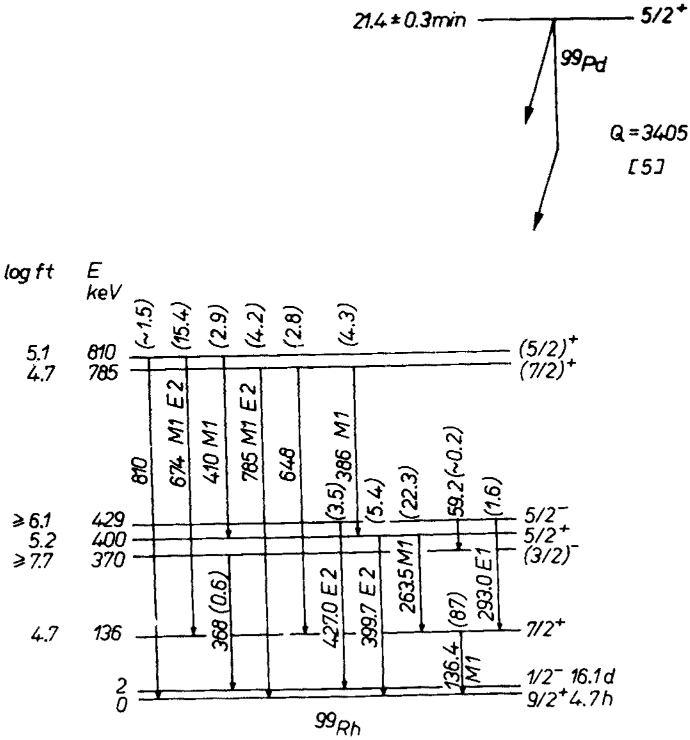

Fig. 7. Proposed decay scheme for ^{99}Pd

785 keV state

This state was introduced on the basis of the discovered $648+136.4$ and $386+400$ keV cascades and 785 keV transition. The intensity ratios for transitions to the $5/2^+$, $7/2^+$ and $9/2^+$ states are I_γ (386 keV): I_γ (648 keV): I_γ (785 keV) $=1.3:2.8:4.2$, and this indicates that the spin of this state is $7/2^+$.

810 keV state

This state was established in study [1] on the basis of coincidences of the 673 and 136 keV transitions, and it is now confirmed by the appearance of the 810 keV transition and the 410–400 keV cascade. The intensity ratio of the branches of this state, I_γ(673 keV$\rightarrow 7/2^+$): : I_γ (810 keV $\rightarrow 9/2^+$) $= 10$, indicate that spin $5/2^+$ is the most probable among the two possible spins, $7/2^+$ and $5/2^+$.

The results of our work concerning the low excited states of ^{99}Rh are, in principle, in agreement with the results of Phelps and Sarantites [5]. But the proposed schemes of excited states are essentially different as regards the position of the 1/2⁻ and 9/2⁺ states. The reason for this discrepancy is that the schemes are based on data from different sources in the literature.

Phelps and Sarantites took the total decay energy of ^{99}Rh (16.1 d) from Ref. [17], the result of which is in disagreement with the newest data on the decay of this state in Ref. [14]. The data on the decay of the 4.7 h state of ^{99}Rh in Refs [13,1] imply an energy gap of 3 ± 30 keV for the $1/2^-$ and $9/2^+$ states, what is contrary to the value of 64.6 keV proposed by Phelps and Sarantites on the basis of ambiguous gamma-gamma coincidences.

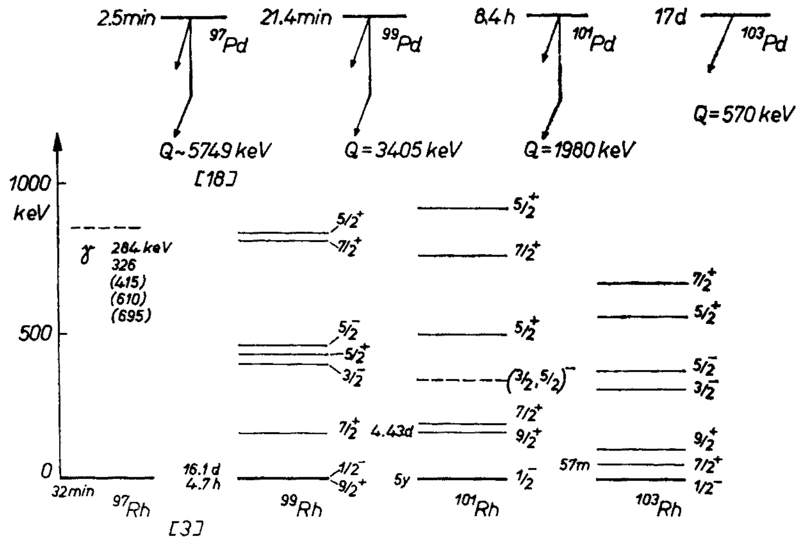

Fig. 8. Low-lying excited states of odd Rh isotopes

On the other hand, placing the E1 293 keV transition between the 429 keV ($5/2^-$) and 136 keV ($7/2^+$) states, in accord with the coincidence between the 136 and 293 keV transitions found in Ref. [5], provides and unambiguous interpretation that the $9/2^+$ (4.7 h) state is the ground state, whereas the $1/2^-$ (16.1 d) state lies at a height of 2.0 ± 0.4 keV.

7. *Excited states of ^{98}Rh*

Up to now, only the isomeric state of ^{98}Rh with $T_{1/2} = 3$ min decaying directly into ^{98}Ru was known. This state is unoccupied during the ^{98}Pd decay [2]. In order to establish the scheme of excited states of ^{98}Rh, the absolute transition intensities were estimated by making a comparison with the 653 keV line in ^{98}Ru, and searches, revealed several cascades:

$$67.8+106.9 = 174.7 \text{ and } 62.5+112.0 = 174.5; \; E_\gamma = 174.6\pm0.2 \text{ keV}.$$

The balance of intensities arranged for the decay scheme proposed in Fig. 9 makes it possible to calculate the value of log ft, assuming the total decay energy to be $Q = 3470$ keV, after Cameron [18]. The spin of the ground state of ^{98}Rh was determined unambiguously in Ref. [1] from measurements of the β^+ spectrum in the decay to the ^{98}Ru excited states.

106.9 keV state

This state is revealed by the existence of the 67.8+106.9 keV cascade and the intensity balance. As the 106.9 keV transition is of the M1 type, while its state is weakly occupied in the β^+ decay ($\log ft \geqslant 7.4$), its spin may be either 2^+ or 3^+.

112.0 keV state

This state is populated in the β^+ decay ($\log ft = 5.1$) and is associated with the ground state by an M1 transition, hence, its spin is 1^+.

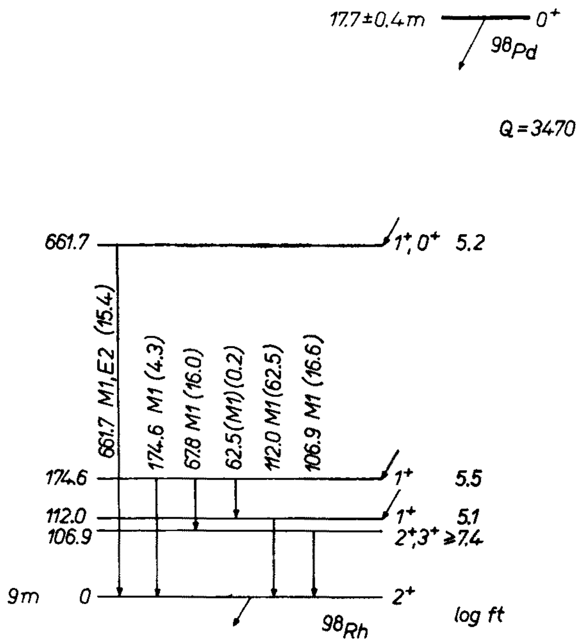

Fig. 9. Decay scheme of ^{98}Pd

174.6 keV state

The position of this state stems from the observed cascades, while the M1 character of these transitions and the allowed β^+ decay ($\log ft = 5.5$) indicate a spin of 1^+.

661.7 keV state

This state is populated directly in the β^+ decay of ^{98}Pd ($\log ft = 5.2$), what implies spin 0 or 1 of positive parity owing to the M1 or E2 character of the 661.7 keV transition.

The occurrence of low-lying excited states of the given spins in ^{98}Rh may be explained similarly as for ^{100}Rh [19] by the Brennan-Bernstein theory [20] as the result of the aggregation of the configuration of 5 protons and 3 neutrons:

$$(g_{9/2})^4(p_{1/2})+(d_{5/2})^{3-n}(S_{1/2})^n \to 2^-, 1^-$$

$$n = 0, 1, 2$$

$$(g_{9/2})^5+(d_{5/2})^{3-n}(S_{1/2})^n \to 2^+, 1^+.$$

By applying this model of coupling it is possible to give a qualitative explanation of the lowering of the two states 2^+ and 1^+ with respect to the states 1^- and 2^-, unobserved in ^{98}Rh, in the transition from ^{100}Rh to ^{98}Rh as due to a change in the mutual position of the proton states $9/2^+$ and $1/2^-$ between ^{101}Rh and ^{99}Rh (Fig. 8). Unfortunately, a full picture of the shifts of the levels cannot be given because of the lack of data on the neutron states in the ^{99}Ru and ^{97}Ru isotopes.

REFERENCES

[1] S. Katcoff, H. Abrash, *Phys. Rev.*, **103**, 966 (1956).

[2] A. H. W. Aten Jr, T. de Vries-Hamerling, *Physica*, **21**, 597 (1955).

[3] M. Gąsior, A. W. Potempa, J. Sieniawski, *Tezisy dokladov IX soveshchaniya po yadernoi spektroskopii*, Dubna, 1–5 iyula 1969, p. 29.

[4] N. M. Antoneva, A. V. Barkov, E. P. Grigorev, M. K. Nikitin, L. F. Protasova, *Tezisy XIX ezhegodnogo soveshchaniya po yadernoi spektroskopii*, Erewan 1969, p. 64.

[5] M. E. Phelps, D. G. Sarantites, *Nuclear Phys.*, **A135**, 116 (1969).

[6] M. Gąsior, H. I. Lizurej, H. Niewodniczański, A. W. Potempa, *Nukleonika*, **13**, 635 (1968).

[7] M. Gąsior, *Postępy Techniki Jądrowej*, **9–10**, 853 (1964).

[8] A. Bałanda, M. Gąsior, H. I. Lizurej, H. Niewodniczański, *Acta Phys. Polon.*, **35**, 301 (1969).

[9] T. S. Nagpal, *Nuclear Phys.*, **A121**, 176 (1968).

[10] J. S. Evans, E. Kashy, R. A. Naumann, R. F. Petry, *Phys. Rev.*, **138B**, 9 (1965).

[11] A. Marelius, H. Pettersson, S. Törnkvist, S.-E. Hägglund, R. Dumitrescu, *Ark. Fys.*, **37**, 435 (1968).

[12] R. S. Hager, E. C. Seltzer, *Internal Conversion Tables*, CALT-63-60.

[13] C. L. Scoville, S. C. Fultz, M. L. Pool, *Phys. Rev.*, **85**, 1046 (1952).

[14] G. A. Moss, D. K. McDaniels, *Phys. Rev.*, **162**, 1087 (1967).

[15] J. L. Black, W. J. Caelii, R. B. Watson, *Nuclear Phys.*, **A125**, 545 (1969).

[16] K. S. Thorne, E. Kashy, *Nuclear Phys.*, **60**, 35 (1964).

[17] C. W. Townley, J. D. Kurbatov, M. H. Kurbatov, *Bull. Amer. Phys. Soc.*, **4**, 366 (1959).

[18] A. G. W. Cameron, *Canad. J. Phys.*, **35**, 1021 (1957).

[19] J. S. Evans, R. A. Naumann, *Phys. Rev.*, **138B**, 1017 (1965).

[20] M. H. Brennan, A. M. Bernstein, *Phys. Rev.*, **120**, 927 (1960).